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THERMAL SIMULATION AND ECONOMIC ASSESSMENT OF UNGLAZED TRANSPIRED COLLECTOR SYSTEMS

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ABSTRACT

Unglazed transpired collectors (UTCs) have recently emerged as a new solar air heating technology [1-4]. They are relatively inexpensive, efficient, and particularly suited to applications in which a high outdoor air requirement must be met. A TRNSYS [5] model has been created for use in simulations to predict the energy savings for UTC systems.

Annual simulations are performed for several representative buildings. The statewide economic potential of UTC systems is assessed for Wisconsin. UTC systems on existing buildings are competitive with electric heating systems, but not with gas or oil heating. Electric heating is not widely-used in most buildings that are well-suited for UTC systems, with the exception of large apartment buildings. Therefore, there is no significant statewide economic potential for retrofit of UTC systems on existing buildings except in the residential sector. However, UTC systems are cost effective for new buildings because their low first cost allows them to compete with gas and oil heating.

1. INTRODUCTION

Renewable energy technologies must do more than be environmentally friendly to be successful; they must also be economically feasible. A failure to meet this second requirement is the reason that many renewable energy technoligies have not gained more widespread acceptance.

In the past few years, unglazed transpired collectors (UTCs), have emerged as a new and promising solar air heating technology. As shown in Figure 1, these collectors consist of a perforated, solar-absorbing plate mounted on a large south-facing wall. Air is drawn through the holes in the plate, into the plenum, and finally into the building. Unlike most solar air heaters, they are not covered by a glazing, which eliminates the reflection losses associated with glazings. UTC systems have achieved higher efficiencies at lower initial costs than current solar air heaters. Furthermore, they have been found to be cost effective in a number of specific applications. The objective of this research is to determine the economic potential of UTC systems on a statewide basis.

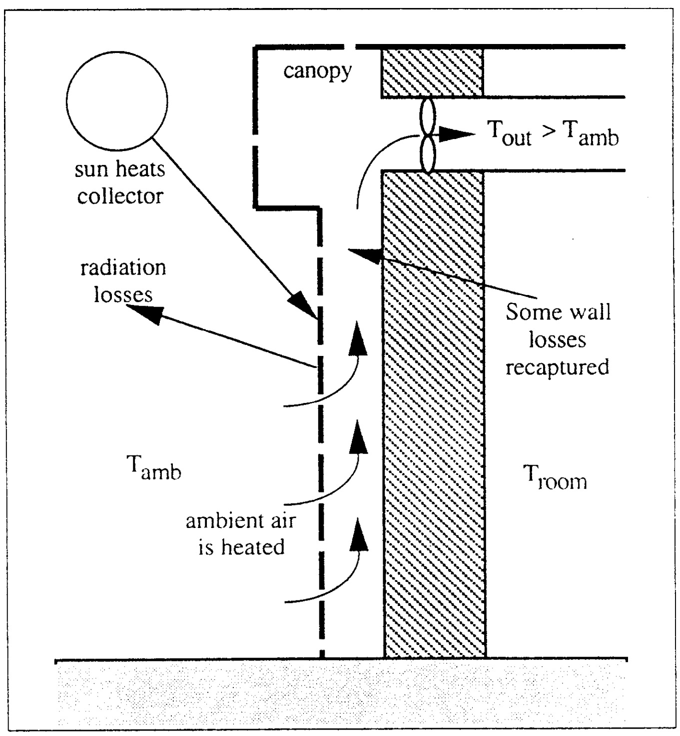

Fig. 1 Schematic diagram of a UTC system.

2. UTC SYSTEM THEORY

The thermal performance of the UTC system is measured by the outlet air temperature from the collector, T_{out}. There are four fundamental energy balance equations that are applicable. These are solved to find T_{out}.

$$\dot{m}_{out}\, c_p\, (T_{plen} - T_{amb}) = \dot{Q}_{conv,col-air} \quad (1)$$

$$\dot{m}_{out}\, c_p\, (T_{out} - T_{plen}) = \dot{Q}_{conv,wall-air} \quad (2)$$

$$\dot{Q}_{cond,wall} = \dot{Q}_{conv,wall-air} + \dot{Q}_{rad,wall-col} \quad (3)$$

$$\dot{Q}_{abs} + \dot{Q}_{rad,wall-col} = \dot{Q}_{conv,col-air} + \dot{Q}_{rad,col-sur} \quad (4)$$

Equations 1 and 2 are energy balances on the air flow from ambient to the plenum and plenum to builidng, respectively. Equation 3 is an energy balance on the outside building wall surface. Equation 4 is an energy balance on the collector plate.The labelling convention that is used for heat flows is $\dot{Q}_{mode,from-to}$. So $\dot{Q}_{conv,col-air}$ is convection from the collector to the air.

In Equation 4, it is assumed that there are no convection losses from the collector to the surroundings. This assumption has been validated analytically if the air flow rate per unit of collector area, or approach velocity, is greater than 0.02 m/s and the collector area is large enough that edge loss is negligible [2].

Rate equations for the energy flows are needed in order to solve the energy balance equations. For convection from the collector to the air, an empirical heat transfer correlation for flow through a perforated plate is used [2].

$$Nu_D = 2.75\ (P / D)^{-1.2}\ Re_D^{0.43} \quad (5)$$

This correlation determines the Nusselt number based on hole diameter and is used to find $h_{conv,col-air}$. Convection occurs on the front surface, the sides of the hole and the back surface of the collector plate. All three areas are included in Kutscher's correlation. The heat exchanger effectiveness of the collector is calculated by Equation 6.

$$\varepsilon_{HX} = 1 - \exp(\ (h_{conv,col-air}\, A_s) / (\dot{m}_{out}\, c_p) \quad (6)$$

This effectiveness is used in the relation between the plenum air temperature and the collector temperature.

$$\varepsilon_{HX} = (\,T_{plen} - T_{amb}\,) / (\,T_{col} - T_{amb}\,) \quad (7)$$

Equations 6 and 7 are used to determine the temperature of the air in the plenum. The following rate equations are also used with the energy balances.

$$\dot{Q}_{conv,wall-air} \quad (8)$$

$$= h_{conv,wall-air}\, A\, (T_{wall} - T_{plen}) \backslash\ O(Q,')_{cond,wall}$$

$$= h_{cond,wall}\, A\, (T_{room} - T_{wall})$$

$$(\dot{Q}_{rad,wall-col} \quad (9)$$

$$= \sigma_{sb}\, A\, (T_{wall}^4 - T_{col}^4) / (1/\varepsilon_{wall} + 1/\varepsilon_{col} - 1) \quad (10)$$

$$\dot{Q}_{abs} = \alpha_{col}\, I_T\, A_s \quad (11)$$

$$\dot{Q}_{rad,col-sur} = \varepsilon_{col}\, \sigma_{sb}\, A_s\, (\,T_{col}^4 - T_{sur}^4\,) \quad (12)$$

Ambient air is heated by the collector and wall to the outlet temperature, T_{out}. The useful energy gained is the sum of convection from the collector and from the outside wall surface.

$$\dot{Q}_u = \dot{Q}_{conv,col-air} + \dot{Q}_{conv,wall-air} \quad (13)$$

The outlet air from the collector is mixed with recirculated air from the building. This air, at T_{mix}, may be further heated to the necessary supply temperature to meet the heating load.

The recirculation damper varies the fraction of the supply air that is drawn from the outside through the collector such that the auxiliary energy is minimized. An energy balance on the entire system yields the auxiliary amount, if any, of the energy required to meet the heating load.

$$\dot{Q}_{aux} = \dot{m}_{out}\, c_p\, (T_{room} - T_{amb}) + \dot{Q}_{bldg} - \dot{Q}_u$$

$$= \dot{Q}_{load} - \dot{Q}_u$$

$$= \dot{Q}_{load} - (\,\dot{Q}_{conv,col-air} + \dot{Q}_{conv,wall-air}) \quad (14)$$

There are three energy savings mechanisms for a UTC system: active solar gain, recaptured wall loss, and reduced wall loss. However, the energy savings of the UTC system is not simply the sum of these three components. Fundamentally, the energy savings are the reduction in the heat required from a traditional system which may haved lower outdoor air flow than the UTC system. The heat required from the auxiliary unit of a UTC system is less than the heat required from a traditional heating system.

$$\dot{Q}_{save} = \dot{Q}_{trad} - \dot{Q}_{aux} \quad (15)$$

So the energy savings never exceeds the heating requirements of the building with a traditional system, and, calculated by Equation 15, can be substantially less than the sum of the three UTC savings components if the UTC system operates above the minimum outdoor air flow rate of the building [6].

3. ECONOMIC THEORY

The total life cycle savings of a UTC system can be calculated by the P_1, P_2 method [7].

$$LCS = P_1\, C_F\, \mathcal{F} Q_{trad} - P_2\, (C_E + C_A\, A) \quad (16)$$

C_F is the cost of fuel, C_E is the fixed equipment first cost, and C_A is the equipment first cost per unit area. The auxiliary heating unit must be able to meet the entire heating load of the building at times when there is no soalr,so there is no equipment cost savings on the traditional unit.

P_1 and P_2 are determined from economic parameters (e.g. interest rate, inflation rate, period of economic analysis). P_1 is the ratio of life cycle fuel savings to first year fuel savings. Typically, for a period of economic analysis of N years, $N/2 < P_1 < N$. P_2 is the ratio of life cycle expenditures to initial investment. Typically, $0.5 < P_2 < 1.0$. This method simplifies the economic analysis by concentrating all of the economic parameters into the two parameters P_1 and P_2.

$\mathcal{F}$ is the solar fraction, defined as the fraction of the traditional load that is met by the solar energy system [7].

$$\mathcal{F} = Q_{save} / Q_{trad} \tag{17}$$

Q_{save} cannot exceed Q_{trad}, as discussed in Section 2, and therefore, the solar fraction cannot exceed unity.

A UTC system is a good investment if the life cycle savings, calculated from Equation 16, are grater than zero. However, only the ratio of P_1/P_2 is needed to determine whether a UTC system is a good investment. Equation 18 yields the minimum ratio P_1/P_2 necessary for the life cycle savings to exceed zero.

$$P_1/P_2 = (C_E + C_A\, A) / (C_F\, Q_{save}) \tag{18}$$

If the ratio P_1/P_2 is greater than the ratio calculated from Equation 18, then a UTC system is a good investment. Equation 18 is also the simple payback period, defined as the amount of time to earn back the first cost of a system in fuel savings.

4. STATEWIDE ANALYSIS

The potential for UTC systems is calculated for several economic sectors in Wisconsin. For each sector the fuel costs and heating requirements are different.

4.1 Fuel and Equipment Costs

The first cost of a UTC system is affected primarily by the type of building on which the system is installed. The collector unit cost is approximately $\$40/m^2$ for installation on a new building and $\$80/m^2$ for retroffit on an existing building retrofit, for a collector area of over 500 m^2 thiat is uninterrupted by windows or doors [8].

The fuel savings depends on the cost of the fuel being replaced. The average cost of fuel for the state of Wisconsin is given in Table 1 [9]. The values are in dollars per unit of heat supplied for the given efficiencies. Natural gas is much cheaper than electricity. Currently the prices of distillate oil and fuel oil are slightly lower than that of natural gas [9], so the life cycle savings for buildings with distillate oil heating is slightly lower than that for buildings with natural gas heating.

TABLE 1. AVERAGE COST OF DELIVERED ENERGY IN WISCONSIN

Fuel Cost ($/GJ)	Natural Gas	Electricity
Efficiency	0.9	1.0
Commercial	5.33	17.89
Industrial	3.72	12.03
Residential	7.27	21.83

4.2 Commercial Sector

Table 2 shows TRNSYS simulation results for four typical commercial buildings in Wisconsin. These buildings are a health/education building, an office building, a retail building, and a warehouse.

The energy savings per unit area are dependent on the building balance temperature. At the balance temperature, the heating load with a traditional heating unit, $\dot{Q}_{trad}$, is equal to zero. Since the energy savings rate cannot exceed $\dot{Q}_{trad}$, there is no energy savings when the ambient temperature is higher than the building balance temperature, even if the summer bypass damper is closed. Therefore, as shown in Table 2, UTC systems on buildings with low balance temperatures save less energy than those on buildings with high balance temperatures. There is little variability in the energy savings in Table 2. In order to extrapolate the results from these simulations to a statewide basis, an average value of $Q_{save}/A = 1.5$ GJ/yr-m^2 is chosen for the commerical sector.

The economic potential is the energy savings and fuel cost savings that result when UTC systems are only used by buildings on which they are economically feasible [10]. Obviously, the economic feasibility of a UTC system depends on its thermal performance. However, for a given thermal performance, there are two factors which affect the economics: the fuel and equipment costs. The life cycle savings are calculated for existing and new buildings with natural gas and electric heating.

TABLE 2. SIMULATION RESULTS FOR TYPICAL COMMERCIAL BUILDINGS IN WISCONSIN

Building	Q_{save}/A [GJ/yr-m^2]	T_{bal} [°C]
A	1.42	13.1
B	1.45	15.0
C	1.53	19.5
D	1.57	19.0

The worst economic case is an existing building (high first cost of collector) with natural gas heating (low fuel costs). For a new building, the equipment costs are less than for an existing building, and thus the life cycle savings is greater. A building with electric heating has a higher fuel cost than one with natural gas heating and the life cycle savings are greater.

Assuming that $C_E = 0$ and $Q_{save}/A = 1.5$ GJ/m^2, the minimum ratio P_1/P_2 which yields a positive life cycle savings is calculated from Equation 18 and shown in Table 3. This ratio P_1/P_2 is also the simple payback period in years.

TABLE 3. MINIMUM P_1/P_2 RATIOS FOR LCS = 0 IN THE COMMERCIAL SECTOR

Building, fuel type	C_A [\$/m^2]	C_F [\$/GJ]	P_1/P_2
New, electric	40	17.89	1.49
Existing, electric	80	17.89	2.98
New, gas	40	5.33	5.00
Existing, gas	80	5.33	10.01

For existing buildings, a UTC system is a good investment only if the building has electric heating. A negligible fraction of commercial buildings in Wisconsin use electric heating [11]. The economics are marginal for new buildings heated with gas. Therefore, UTC systems do not have a significant statewide potential for use on existing buildings in the commercial sector. However, UTC systems should be considered for new commercial buildings in Wisconsin.

4.3 Residential Sector

The minimum outdoor air requirement of a single-family dwelling is not large enough to allow operation of a UTC system because the minimum approach velocity limits the collector to a small area. However, a multi-family dwelling may have a large enough outdoor air requirement for a UTC system. The outdoor air requirement for a residential building is 0.35 air changes per hour (ACH) but not below 15 cfm/person [12]. A townhouse building in Madison, WI, that houses four families is of three poeple is chosen as a model. The required 0.35 ACH yields an outdoor air flow rate below 15 cfm/person, so the outdoor air requirement for the townhouses is 180 cfm = 0.085 m^3/s. An approach velocity of 0.035 m/s is chosen, yielding a collector area of 2.4 m^2. The TRNSYS simulation shows that the UTC system energy savings are 1.56 GJ/m^2, which is comparible to those for commercial buildings (see Table 2). The collector area for the townhouses is too small to operate a UTC system with maximum efficiency, but a UTC system on a large apartment building would have a large enough collector area to be efficient.

Using $C_E = 0$ and $Q_{save}/A = 1.5$ GJ/m^2, the minimum ratio P_1/P_2 which yields a positive life cycle savings is calculated from Equation 18 and shown in Table 4.

TABLE 4. MINIMUM P_1/P_2 RATIOS FOR LCS = 0 IN THE RESIDENTIAL SECTOR

Building, fuel type	C_A [\$/m^2]	C_F [\$/GJ]	P_1/P_2
New, electric	40	21.83	1.22
Existing, electric	80	21.83	2.44
New, gas	40	7.27	3.67
Existing, gas	80	7.27	7.34

UTC systems may have a significant statewide potential for use in the residential sector on existing large apartment buildings that have electric heating. It is difficult to determine the magnitude of the potential because statewide data are not available on the number of large apartment buildings with electric heating. UTC systems should also be considered for new large apartment buildings with gas or electric heating.

4.4 Agricultural Sector

The feasibility of using UTC systems to pre-heat ventilation air for poultry and livestock shelters are explored. UTC systems for crop drying and storage were not considered.

UTC systems on swine shelters were simulated for two cases: a shelter with only growing pigs and a shelter with only adult pigs. A ventilation rate of 0.001 m^3/s-sow is used for the growing pigs and 0.01 m^3/s-sow for the adult pigs [13].

A face velocity of 0.04 m/s is chosen, which yields collector areas of 0.025 m^2/sow for the growing pigs and 0.25

m^2/sow for the adult pigs. Since UTC systems require large collector areas to operate at maximum efficiency, only large farms are well-suited for UTC systems. Over 90% of the swine farms in Wisconsin have less than 500 pigs [14]. For these small farms, as with single-family residences, the collector area is not large enough to operate a UTC system.

The lowest optimum temperature is 10 °C for adult swine and varies with age for growing pigs [13]. An average value for growing pigs is 20 °C. However, the balance temperature is higher for shelters with adult pigs than for those with growing pigs, as shown in Table 5. The growing pigs generate about 100 W/pig, and the adult pigs generate about 250 W/pig [13]. More growing pigs than adult pigs can be housed in the same building: it is assumed that five 18-kg growing pigs need the same space as an adult pig. Therefore, the internal gain in a shelter for growing pigs is high, causing a low balance temperature. The balance temperatures in Table 5 are highly-dependent on the shelter UA-value, but for any reasonable UA-value the balance temperature of the growing-pig shelter is lower than for the adult-pig shelter.

TABLE 5. SIMULATION RESULTS FOR UTC SYSTEMS ON SWINE SHELTERS

Swine	Q_{save}/A [GJ/m^2]	T_{bal} [°C]
Growing pigs	0.64	-1.5
Adult gilt, sow, or boar	0.80	1.5

As shown in Table 5, both swine shelter simulations yield low energy savings due to the low balance temperatures. The energy savings in Table 5 are aabout one-half the values for the commercial sector (see Table 2). UTC systems do not have a significant statewide potential for use on swine shelters due to the low energy savings and the need for large collector areas.

Dairy cows, beef cattle, and poultry are productive in low temperatures [13]. Simulations of UTC system on shelters for these animals were not performed, but it is expected that there is little significant statewide potential for use of UTC systems on livestock or poultry shelters.

4.5 Industrial Sector

Statewide data are not readily available to estimate the technical potential of UTC systems in the industrial sector. Regardless of the technical potential, the economic potential of UTC systems in the industrial sector is insignificant.

Many industrial buildings have a low balance temperature due to a low room temperature or significant heat generation internally from industrial processes. As with livestock shelters, a low balance temperature yields a low energy savings.

Significant energy savings on industrial buildings is possible if they have a high balance temperature and high outdoor air requirement. However, this energy savings does not translate into life cycle savings unless the building uses electric heating, as shown previously. Since a negligible fraction of industrial buildings use electric heating [11], there is no significant economic potential for UTC systems in the industrial sector.

5. CONCLUSIONS

The performance of UTC systems have been simulated using a simple energy balance model that is described in Section 2. Annual simulations are performed with the TRNSYS component subroutine.

A statewide impact study is based on the P_1, P_2 method of life cycle savings. There appears to be little statewide economic potential for UTC systems in Wisconsin in the commercial, agricultural, and industrial sectors. The reason is that UTC systems on existing buildings can only compete with electric heating, and electric heating is not widely used in buildings which are well-suited for UTC systems. In the residential sector, UTC systems are economically feasible for existing large apartment buildings with electric heating. UTC systems should also be considered for new buildings where their low first cost allows them to compete economically with gas and oil heating.

6. NOMENCLATURE

A	total collector area (m^2)
A_s	collector surface area (m^2) = $(1-\sigma)$ A
C_A	UTC system cost per unit collector area ($/$m^2$)
C_E	UTC system fixed cost ($)
C_F	fuel cost ($/GJ)
c_p	specific heat (J/kg-K)
D	hole diameter (m)
$\mathcal{F}$	solar fraction
$h_{cond,wall}$	coefficient for conduction through the wall (W/m^2-K)
$h_{conv,col-air}$	coefficient for convection from the collector to the air (W/m^2-K)
$h_{conv,wall-air}$	coefficient for convection from the outside wall surface to the air (W/m^2-K)
I_T	incident solar radiation on the collector surface (W/m^2)
LCS	life cycle savings ($)

$\dot{m}_{out}$	collector outlet air mass flow rate (kg/s)
Nu_D	Nusselt number where D is the characteristic length
P	hole pitch (m)
P_1	ratio of life cycle fuel savings to first-year fuel savings
P_2	ratio of life cycle capital expenditures to initial investment
Q_{save}	annual energy saved (GJ/yr)
$\dot{Q}_{abs}$	absorbed solar heat rate (W)
$\dot{Q}_{aux}$	auxiliary heat rate (W)
$\dot{Q}_{bldg}$	building heat loss rate (W)
$\dot{Q}_{cond,wall}$	conduction rate through the wall (W)
$\dot{Q}_{conv,col\text{-}air}$	convection rate from the collector to the air (W)
$\dot{Q}_{conv,wall\text{-}air}$	convection rate from the outside wall surface to the air (W)
$\dot{Q}_{load}$	total heating load rate (W)
$\dot{Q}_{rad,col\text{-}sur}$	radiation rate from the collector to the surroundings (W)
$\dot{Q}_{rad,wall\text{-}col}$	radiation rate from the outside wall surface to the back of the collector (W)
$\dot{Q}_{save}$	saved energy rate (W)
$\dot{Q}_{trad}$	traditional heating system heat rate (W)
$\dot{Q}_u$	useful energy rate (W)
Re_D	Reynolds number where D is the characteristic length
T_{amb}	ambient air temperature (K)
T_{bal}	balance temperature (°C)
T_{col}	collector plate temperature (K)
T_{out}	collector outlet air temperature (K)
T_{plen}	plenum air temperature (K)
T_{room}	room air temperature (K)
T_{wall}	outside wall surface temperature (K)
UA	total UA for walls and roof (W/K)
α_{col}	collector plate absorptivity
ε_{col}	collector plate emissivity
ε_{HX}	heat exchanger effectiveness of collector
ε_{wall}	outside wall surface emissivity
σ	collector porosity
σ_{sb}	Stefan-Boltzmann constant ($W/m^2\text{-}K^4$)

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